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Printed piezoelectric materials for vibration-based damage detection

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Abstract

Piezoelectric materials are of high interest for many applications, e.g. vibrations measurement, active vibration control or vibration-based damage detection in Structural Health Monitoring (SHM). In this paper, thin electroded microceramics of piezoelectric material are straightforward fabricated thanks to the association of the screen-printing technology to the sacrificial layer method. After subsequent printing and drying of a stack of sacrificial, Au, PZT and Au layers on a substrate, piezoelectric disks are fired at 900°C and then released from the substrate. Studies of the electromechanical behaviour of these components obviously show the influence of the sacrificial layer composition on their densification and consequently their piezoelectric properties, favourable for detection of vibrations and SHM applications. Moreover, printing process might lead to lower cost of microceramics implementation than traditional ceramic process.

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Keywords: Screen-printed, PZT, sacrificial layer, densification, vibration sensing, SHM

1. Introduction

Among piezoelectric materials, PZT is usually preferred for MEMS applications because of its higher electromechanical properties. Though bulk or surface micromachining piezoelectric components give satisfactorily results for integrated MEMS, printed PZT thick-films (1-100 µm) seem to be a good alternative solution when sensing/actuating are required at efficient fabrication cost. However, the high porosity of PZT layers was responsible of lower piezoelectric properties of free-standing piezoelectric components compare to those of ceramic [1]. In this paper, using a composite and a polymer as sacrificial layers, implementation of screen-printed PZT piezoelectric microceramics is performed. Afterwards, performances of these printed piezoelectric materials are compared to those of commercial PZT ceramics. Detections of vibrations and damage are finally led with printed piezoelectric ceramics to show the efficiency of these materials in such applications.

2. Experimental

2.1. Previous processing

Processing of free-standing thick-films has been applied to the fabrication of microsystems based on different inorganic materials. Free-standing cantilevers have been successfully processed, with copper and silver for thermal actuators [2] and for force sensors [3], without significant deformations. For this process, a sacrificial layer made of a composite ($SrCO_3$-epoxy) is first printed and cured 25 min at 150 °C prior to the screen-printing and drying of the structural layers (Fig. 1). Then, depending on the layer's nature, the samples are fired between 850°C and 900°C under dry air and finally immersed in the 0.9mole.l-1 H_3PO_4 aqueous solution. This harmlessness and efficient process has also been applied for the fabrication of piezoelectric bridges and cantilevers electroded PZT [1]. In the present work, discrete Au/PZT/Au disks are fabricated and must be totally released from the substrate. The three pastes (Au, PZT, $SrCO_3$-epoxy) and the process selected for the fabrication of such disks are identical to those used for the processing of PZT cantilevers. The screen-printed sacrificial layer covers entirely the 2.5×2.5 cm^2 alumina substrate. After printing and solvents evaporation, the gold and PZT thickness are 5 and 200 µm respectively. In order to limit the presence of cracks or holes in the PZT layer, the drying step is performed with a heating rate of 1°C/min within the 30 to 400ºC temperature range followed by an heating-rate of 20°C/up to 900ºC. The samples are then sintered 2 hours at 900°C prior to go down to room temperature at a cooling rate of -20°C/min. From the resonance frequencies measurements of free-standing samples, it is possible to calculate the piezoelectric parameters such as the dielectric constant (K_{33}^T), the electromechanical coupling factor and the piezoelectric coefficient [4]. Comparison of these parameters is made with those of pellets fabricated with the same PZT composition and fired also at 900°C (Table 1). The lower electromechanical and dielectric properties of the free-standing samples is attributed to the high porosity (30%) of screen-printed PZT layers. This may be explained by the differential shrinkage associated to the chemical reactions and/or different thermal expansion coefficients of Au, Al_2O_3 and inorganic (PZT, $SrCO_3$) powders during the firing process. Indeed, improvement of the densification by addition of a low amount of eutectic phases to the PZT ink is not sufficient for free-standing layers. Actually, one has also to consider the limited shrinkage of thick-films since they are more or less "chemically bound" to the sacrificial layer during the firing process.

a) b) c)

Fig. 1: Processing of a Au/PZT/Au disk (a) cross section of the multilayer structure before co-firing (b) photograph of an alumina substrate with the screen-printed disks before firing (c) photograph of one PZT microceramic after firing and release after removal of the sacrificial layer.

2.2. New processing

To reduce the interactions with the sacrificial layer, the composite ($SrCO_3$-epoxy) sacrificial layer is replaced by a polymer. The same fabrication steps are applied for the microceramics. Instead of the printing of the $SrCO_3$ composite sacrificial layer, a commercial polyester paste type (ESL 244T from ElectroScience Laboratory) is printed and cured 15 min at 120°C . Once co-fired, the disks are released spontaneously from the substrate without any supplementary sacrificial layer etching. Moreover, the use of this new sacrificial layer clearly allows a better shrinkage of the PZT microceramics. The higher densification observed on figure 2 is in accordance with the better electromechanical properties measured on the PZT disks (table 1). The obtained properties compare well to those of the ceramics and offer opportunities for vibration-based damage detections.

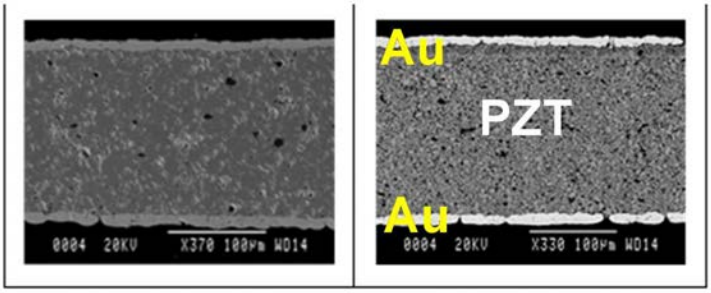

Fig. 2. SEM microsection of printed Au/PZT/Au fired disks, (left) with $SrCO_3$ -epoxy composite and (b) with polymer 244T

Table 1: Comparison of the properties of the printed disks and ceramic one

Sample	Density ($kg.cm^{-3}$)	Lateral shrinkage (%)	K^{33}_T	k_p (%)	d_{31} (pC/N)
Printed Au/PZT/Au / $SrCO_3$-epoxy/Al_2O_3 (∅9.5mm, thickness 190µm)	5	5	600	15	40
Printed Au/PZT/Au / polymer 244T/AlN (∅9.5mm, thickness. 190µm)	7	15	100 0	45	100
Commercial ceramic PIC 151 ∅10mm, Thick. 300µm	8	-	700	65	210

3. Vibration-based damage detection

The fabricated piezoelectric disks are finally tested for vibration detection and vibration-based damage detection. For all the tests, the disks are bonded on a beam with a 30µm-thick rigid silver paste (EPOTECK EPO-TK-E4110). The beams are mounted to a support in different conditions (clamped-free or clamped-clamped) (Fig. 3). In parallel, beams with disks from PI (Physik Instrumente) are manufactured to compare the performances of the fabricated piezoelectric disks to those of commercial disks. Two kinds of tests are performed: vibrations measurement tests to evaluate the efficiency of piezoelectric disks to detect vibrations and EMI (ElectroMechanical Impedance) measurements to evaluate the efficiency of piezoelectric disks for vibration-based damage detection.

For the vibrations measurement tests with the clamped-free beams, the beam is moved away from its equilibrium position and the induced vibrations are used to measure the first resonance mode of the beam (Fig. 4). The difference of magnitude between the measured time signals is due to the difference of thicknesses and d_{31} coefficients of the PZT disks. For both, printed and commercial microceramics, the resonance frequency can be computed with accuracy by FFT of the measured vibrations and the results are similar for both sensors. These tests thus demonstrate that Au/PZT/Au printed disks can be used as sensors for vibrations measurements.

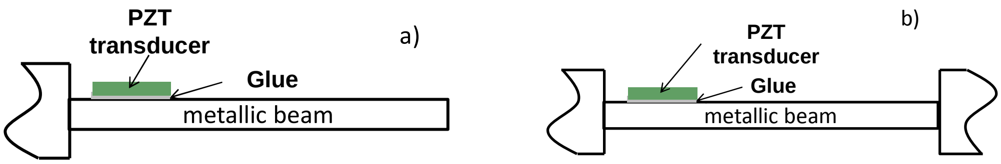

Fig.3: Test devices with the bonded printed Au/PZT/Au disk for (a) vibration test and (b) SHM test ; beam dimensions are 200×20×0.48 mm^3

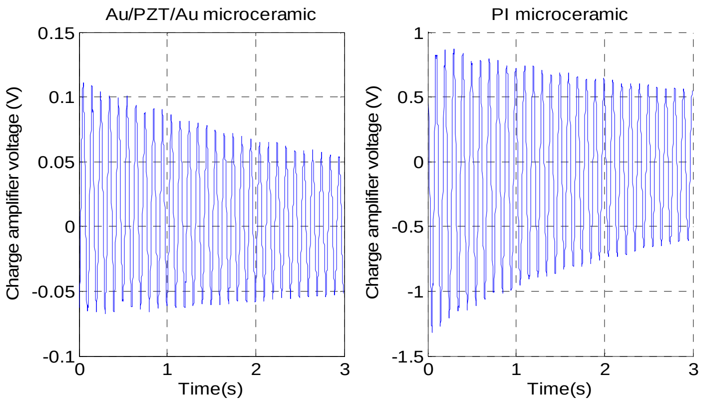

Fig. 4. Output voltages of the charge amplifier for (left) printed Au/PZT/Au on $SrCO_3$-epoxy sacrificial layer and (right) PI microceramics after pulling excitation of the test device.

The second kind of tests concerns Structural Health Monitoring (SHM) which propose attractive tools for structural damage detections [5,6]. Here, the reverse piezoelectric effect of the PZT transducers enables the production of an exciting signal. On the other side, thanks to the direct piezoelectric effect, PZT transducers are able to detect signal variations induced by structural deformation and/or structural damage. This actuating/sensing mode of the piezoelectric transducers is based either on Lamb-wave propagation [7] or electromechanical impedance (EMI) methods [8]. In this work, the piezoelectric Au/PZT/Au microceramic is tested using the EMI method. When the structure is excited with the microceramic, the current generated within the same microceramic and shunted in a resistor allows the calculation of the impedance. Experiments are performed on an undamaged structure at $10<f(kHz)<30$. Damage is simulated by modifying the stiffness and mass of a beam by means of adding a mass on the tip of the beam. In the case of the Au/PZT/Au on $SrCO_3$-epoxy sacrificial layer, the EMI signature is not satisfactory for SHM application (Fig. 5a) whereas with the polymer 244T sacrificial layer, the EMI signatures of the undamaged and damaged structures are clearly discernible and show many resonance peaks which are favorable for SHM applications (Fig. 5b). Indeed, damage detection and localisation are obtained from the evaluation of damage indexes based on EMI variations [9] such as the mean frequency shift of the resonance peaks ($\mathbf{\Delta f_{mean}}(\%)$) defined by :

$$\Delta f_{mean}(\%) = \frac{\sum_{n=1}^{N_{pks}} |f_n^D - f_n^{UD}|/f_n^{UD}}{N_{pks}} * 100\% \tag{1}$$

where f_n^{UD} is the modal frequency of the undamaged structure for mode n, f_n^D the modal frequency of the damaged structure for mode n and N_{pks} the number of modal peaks in the studied frequency band.

From these experimental results, the potentiality of printed Au/PZT/Au piezoelectric microceramics for SHM applications is thus validated.

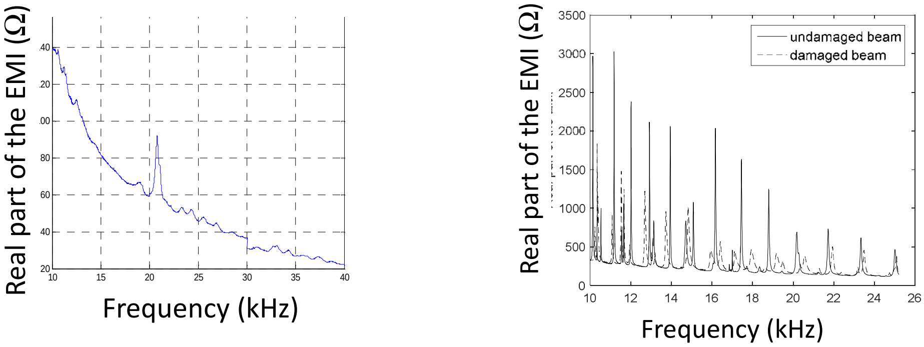

Fig. 5: Real part of the EMI measurements with the Au/PZT/Au microceramic disks, a) fired on $SrCO_3$ sacrificial layer and bonded on the undamaged beam and b) fired on polymer 244T sacrificial layer bonded on the undamaged and damaged beam.

4. Conclusion

The thick-film sacrificial layer process described in this paper may well open new routes of research and technology for printed microceramics. The efficiency of this simple and low-cost process has been demonstrated with the fabrication of microcomponents based on different ceramics, glass or glass-ceramics including piezoelectric materials. We were interested in this paper in the processing of complete released PZT microceramics disks. By modifying the initial sacrificial layer, from a composite composition ($SrCO_3$-epoxy) to a ESL244T polyester type, higher densification and piezoelectric properties of the Au/PZT/Au disks have been obtained. A corresponding planar electromechanical coefficient of 45% has been measured. This value is three times higher than that obtained with the initial process and approaches that of the commercial PI sample. It was demonstrated that these Au/PZT/Au disks can be used as actuator or vibration sensors. When bonded on a metallic structure, their good electromechanical properties are promising for SHM applications based on vibration-based damage detection.

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References

[1] H. Debéda, P. Clément, E. Llobet, C. Lucat H. Debéda, "One-step firing for electroded PZT thick-films applied to MEMS", Smart Mater. Struct. 24 (2015) 025020.
[2] P. Ginet, C. Lucat ., and F.Ménil, "Modelling and characterization of screen-printed metallic electrothermal microactuators", in International Journal of Advanced Ceramic Technology, vol 4, 2007,- pp. 423- 427
[3] R. Lakhmi, H. Debéda, I. Dufour and C. Lucat, "Force sensors based on screen-printed cantilevers", in IEEE Sensor; vol 10, 2010, pp.1133–1137.
[4] B. Jaffe, W.R. Cook and H. Jaffe, 1971, Piezoelectric Ceramics, Academic Press
[5] V. Giurgiutiu, 2008, "Structural health monitoring with piezoelectric wafer active sensors New York: Elsevier Academic Pres
[6] H. Van der Auweraer and B. Peeters," Sensors and systems for structural health monitoring", J. Struct. Control 10 2003, pp.117–125
[7] S. S. Kessler, S. M. Spearing, C. Soutis, "Damage detection in composite materials using Lamb wave methods", Smart Materials and Structures, 11(2), 2002, pp.269.
[8] P. Selva, O. Cherrier, V. Budinger, F. Lachaud and J. Morlier, "Smart monitoring of aeronautical composites plates based on electromechanical impedance measurements and artificial neural networks", Engineering Structures, 56, 2013, pp. 794-804.
[9] O. Cherrier, P. Selva, V. Pommier-Budinger, F. Lachaud and J. Morlier, "Damage localization map using EMI spectrums and IDW interpolation: Experimental validation on thin composites structures", Structural Health Monitoring, 12 (4), 2013, pp. 311-324